Nomination for recognition of the

Sydney Opera House –
the engineering achievements and technological innovation in its design and construction,

as an

Engineering Heritage International Marker

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Revised: March 2021

Michael Clarke
for Engineering Heritage Australia (Sydney)
November 2020

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The Administrator
Engineering Heritage Australia
Engineers Australia
Engineering House
11 National Circuit
BARTON ACT 2600

Herewith is the nomination of:

Sydney Opera House –
engineering achievements and technological innovation in its design and construction

for the award of an Engineering Heritage International Marker.

Location:
Bennelong Point, Sydney; 33.8568° S, 151.2153° E.

Owner:
Government of New south Wales

The Chief Executive Officer of the Sydney Opera House has been advised of this nomination and a letter of support is below.

Access to Sites:
Exterior of building and box office foyer are accessible to the public. Other areas are accessible with guides or subject to security clearance.

Nominating Body:
Engineering Heritage Sydney

Contact:
If you have any queries relating to this nomination, our contact is Michael Clarke, at: m.clarke32@optusnet.com.au

Regards

Frank Johnson
Chair, Engineering Heritage Sydney
Engineers Australia, Sydney Division
16 November 2020

12 November 2020

Michael Clarke
Engineering Heritage Committee
Sydney Division
Engineers Australia
Mezzanine Level, 44 Market Street
Sydney NSW 2067

Dear Mr Clarke

The Sydney Opera House Trust supports the Sydney Engineering Heritage Committee nomination for Engineers Australia to recognise the significance of the Opera House's structural work with an Engineering Heritage International Marker. This is on the basis that, if successful, a non-physical digital plaque would be provided to the Trust. Installation of a physical metal plaque cannot be supported as this would be considered intrusive under the Opera House's Conservation Management Plan.

The Opera House is a landmark not only for Sydney, but for the world, and is included on the UNESCO World Heritage List. It is a masterpiece of inspiration and imagination, built on the foundations of complex and innovative engineering. This icon hosts almost 11 million visitors in a normal year, with more than 1,800 performances attracting 1.4 million attendees. None of this would be possible without the incredible engineering feats that enabled the building's construction.

An Engineering Heritage International Marker would be an important acknowledgement of the engineering profession's significant contribution to the creation of the Opera House.

Yours sincerely

Louise Herron
Chief Executive Officer

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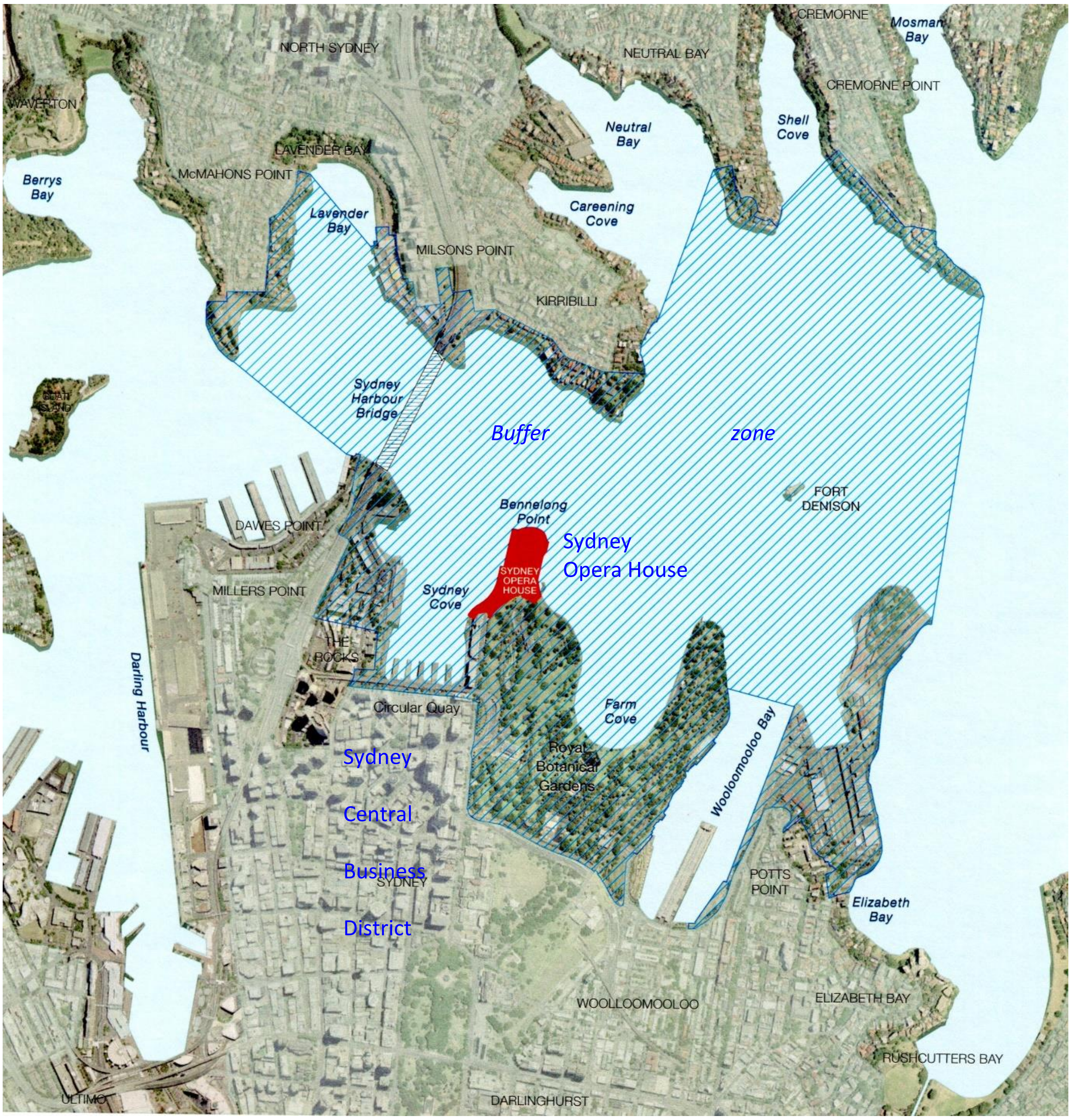
Basic Data

Work:	Sydney Opera House Bennelong Point Sydney New South Wales Australia. Map reference: 33.8568° S, 151.2153° E
Owner:	Government of New South Wales.
Current Use:	Performing arts complex.
Former Use:	Performing arts complex.
Designer:	Jørn Utzon, architect; Ove Arup & Partners, structural engineers.
Maker/Builder:	Civil & Civic Contractors Pty Ltd for foundations and podium (Stage 1). M. R. Hornibrook (NSW) Pty Ltd for concourse, roof and interior (Stages 2 and 3).
Year Started:	1959
Year Completed:	1973
Physical Description:	The Sydney Opera House is an exceptional building composition. Its architectural form comprises three groups of interlocking vaulted 'shells', set upon a vast terraced platform ('the podium') and surrounded by terrace areas that function as pedestrian concourses. The shells are faced in glazed off-white tiles while the podium is clad in earth-toned, reconstituted granite panels. The two main halls are arranged side by side, oriented north-south with their axes slightly inclined. The auditoria are carved out of the high north end of the podium so that they face south towards the city, with the stage areas positioned between them and the entrance foyers. The north and south ends of the shells are hung with topaz glass walls that project diagonally outwards to form foyers, offering views from inside and outside. The tallest shell reaches the height of a 20-storey building above the water. The shell structures cover nearly two hectares and the whole site is nearly six hectares. (World Heritage Nomination).
Physical Condition:	Excellent
Modifications:	2009 - First major upgrade with refurbishing the western foyer 2015 - An underground loading dock completed



Sydney Opera House – location and buffer zone

Source: World Heritage Nomination

The Sydney Opera House – the engineering achievements and technological innovation in its design and construction

1. Introduction

"This, without question, must be the most innovative, the most daring, the most dramatic and in many ways, the most beautiful home constructed for the lyric and related muses in modern times", wrote the music critic of the *Los Angeles Times*.

"This Sydney Opera House was a voyage of architectural and engineering discovery in which new oceans were charted, new frontiers of knowledge and technology were conquered, and the resources of science and technology were employed to solve design, erection and quality of finish problems beyond the capacity of conventional method". Australian architectural historian Max Freeland.

"It stands by itself as one of the indisputable masterpieces of human creativity, not only in the 20th century but in the history of humankind." Expert evaluation report to the UNESCO World Heritage Committee, 2007.

"The Sydney Opera House is a masterpiece of late modern architecture and an iconic building of the 20th century. It is admired internationally and treasured by the people of Australia. Created by an architect who had been an avid sailor and understood the sea, the Sydney Opera House inhabits the world-famous maritime location on Sydney Harbour with such grace that it appears that the building belongs there naturally. The massive concrete sculptural shells that form the Sydney Opera House's roof appear like billowing sails filled by the sea winds with the sunlight and cloud shadows playing across their shining white surfaces. As its Danish architect Jørn Utzon envisaged, 'it is like a Gothic cathedral that people will never tire of and 'never be finished with' [Utzon 1965a: 49]".[1]

"The Sydney Opera House represents a rare and outstanding architectural achievement: structural engineering that stretched the boundaries of the possible and sculptural architectural forms that raise the human spirit. It not only represents the masterwork of Utzon but also the exceptional collaborative achievements of engineers, building contractors and other architects. The Sydney Opera House is unique as a great building of the world that functions as a world-class performing arts centre, a great urban sculpture and a public venue for community activities and tourism. This monumental building has become a symbol of its city and the Australian nation. The Sydney Opera House 'is not a simple entity... [but] alive with citizens and urbanity [Domicelj 2005]".[2]

The idea for a Sydney performing arts centre - which had often been discussed, was given impetus by Sir Eugene Goossens who arrived in 1947 to take up the position of conductor of the Sydney Symphony Orchestra. (A Sydney Opera House timeline is at Appendix A)

The Hon. J.J. Cahill, the Labor Premier of New South Wales was another key advocate and in 1955 he announced that an opera house would be built on Bennelong Point, a headland jutting out into Sydney Harbour and the eastern arm of Sydney Cove, the nation's birthplace.

In February 1956 an international competition was announced for a National Opera House at Bennelong Point. The winning entry by Danish architect Jørn Utzon, was announced in

January 1957; it comprised 12 drawings that featured the now well-recognised sail-like roofs. Without any design drawings or solutions to complex problems, the cost was estimated at £3.5 million.

In their report, the judging panel of four eminent architects said:

> "We have returned again and again to the study of these drawings and are convinced that they present a concept of an Opera House which is capable of becoming one of the great buildings of the world," and, "Because of its very originality, it is clearly a controversial design. We are however, absolutely convinced of its merits".[3]

Ove Arup & Partners was formally engaged as consulting structural engineer for the project in mid-1957.[4] "In an arrangement that would ultimately doom Utzon, the government insisted not only that Arup's contract be directly with the Premier of NSW to whom he would be responsible, rather than to the architect, but also that any specialist consultants would be responsible to Arups, not Utzon".[5]

The estimated cost soon caused controversy, because at the time there were some who considered it a huge expense to spend on the performing arts. Becoming concerned that the project could be overturned by political objections or if there was a change in government, the Premier ensured commitment to the project by ordering commencement, even though there was no accurate geological survey, and before design problems had been solved - including that of the roof whose weight was unknown. (In the event, the forced early start led to significant later problems, not least of which was the fact that the podium columns could not support the roof structure and had to be re-built).

Civil and Civic Pty Ltd, the contractors for Stage 1 – foundations and podium, commenced construction on 2 March 1959.

The relationship required between architect and engineer to achieve a successful outcome and to which Arups adhered, has been described by John Nutt of Arups as follows:

> "During the design development phase, the architect and the engineer work closely together to understand each other's problems. Strict adherence to architectural intent can result in an 'unbuildable' structure. Unsympathetic engineering can debase the architect's concept. Mutual reliance and support have to be so close that the integration of design makes it impossible to separate the contributions of each".[6]
>
> However, in his Introduction to the *Sydney Opera House,* Arup and Zunz*,* Jack Zunz said:
>
> "I don't think that he [Utzon] ever really understood the complexity of the problems he was creating. Nor do I believe that he understood the problem-solving processes which ensued when new technology had to be developed, or even when existing technology had to be adapted for new and untried forms. It is just possible that, in his seeming blindness to see that his collaboration with us was vital for the technical success of the scheme, lies another factor in his urge to leave the job".[7]

Cost escalations and completion-time blow-outs dogged the Opera House from its beginning with complexities being revealed as design progressed, and as delays occurred in the production of drawings. With the change to a conservative Liberal-Country Party government in May 1965, Davis Hughes the new Minister for Public Works was determined to rein in costs. Relations with the government soured when Hughes refused Utzon's fee

claims and his request to provide funding for construction of prototypes to test large plywood beams to carry the ceiling, and of plywood for the mullions for the glass walls.

'Arup's protection [from an impatient government] had long given Utzon a false sense of security in his pursuit of perfection whatever the cost, also involved concealing from the government for many years (and many millions of dollars) what it belatedly acknowledged was 'chaos' as Utzon's 'cavalier approach to costs began to cause endless friction' between them. This attitude was evident in Utzon's demand about solving the roof problem: 'I don't care what it costs. I don't care how long it takes. I don't care what scandal it causes. That is what I want".[8]

Eventually, Utzon resigned in frustration on 14 March 1966, and on 19 April Davis Hughes appointed a panel of Australian architects to complete the Opera House: Peter Hall in charge of design, David Littlemore in charge of supervision, and Lionel Todd in charge of documents.

Utzon and his family left Australia on 28 April, with Utzon never to return.

The Opera House was opened by Queen Elizabeth II on 20 October, 1973. The final cost in dollars of the day was $102 million, and was largely paid for by a State Lottery.

Major contributory features that establish the world-renown of the Opera House and attract interest and visitation, are the structural elements and the story of the engineering genius that made a reality, a virtually impossible conceptual building – the outcome is as much an engineering masterpiece as an architectural one.

The design and construction of the Sydney Opera House was of the highest complexity in all its aspects – architectural design, structural design, selection of materials, erection of the shell roofs, survey control, and in other areas. It required patience, dedication, expertise, skill and ingenuity of all involved.

While the 'fan' of rib roofs rising from the pedestals can be marvelled at in the foyers, and the great folded beams can be appreciated in the lower concourse, it is an unfortunate necessity that the beautiful spherical matrix-like geometry of the unclad rib-roof is hidden by the tile lids, and that their underside - the soaring ribs, is largely hidden by the ceilings.

This nomination is about the engineering achievements and the technological innovation in the design and construction of the Sydney Opera House without which it would not have become a reality in its present form. As well as other sources, it draws extensively on:

- *Sydney Opera House* – a paper by Ove Arup and Jack Zunz with Introduction by Jack Zunz, The Arup Journal, October 1973, https://www.arup.com/perspectives/publications/the-arup-journal/section/the-arup-journal-1973-issue-3#
- *Building a masterpiece: the Sydney Opera House*, Powerhouse Publishing 2006;
- *Sydney Opera House: Nomination by the Government of Australia for inscription on the World Heritage List 2006; and*
- *Opera House Act One,* 1997, by David Messent.

For simplicity, the first three are denoted in endnotes as:

- *Sydney Opera House,* Arup and Zunz
- *Building a masterpiece;* and
- *World Heritage Nomination*

From the outset, the roofs of the Opera House were described as 'shells' because they were conceived as being of thin concrete. Ultimately, the roofs were constructed from large concrete ribs joined together. As many of the authors quoted have described the roofs as 'shells', throughout this nomination the terms 'shells' and 'roofs' are interchangeable

2. Statement of Significance

The Sydney Opera House is of outstanding universal value as a masterpiece of both 20th century architecture and of structural engineering and technological innovation.

It has high scientific and technical significance for the ways in which its design and construction continually pushed engineering and building technologies to the limit, and for the many innovations which have since influenced structural design. The Opera House could not have been created in its present form without the outstanding creative and pioneering engineering contribution of consulting engineers Ove Arup & Partners, and the builders M. R. Hornibrook Pty Ltd.

The Sydney Opera House:

- was the first computer-designed building of significant scale; it could not have been built without the use of computers;
- involved the first example of factory manufacture and erection of large precast concrete units of complex geometry;
- involved the earliest example in the world of epoxy jointing of matched concrete segments;
- was the first large-scale use of laminated glass walls and roofs; and
- used an erection arch for construction of the roofs that was the most complex piece of scaffolding used in the construction industry in Australia.

The folded beams under the monumental steps, the roof ribs and their pedestals, the tile lids, and the glass walls, are integral to the Sydney Opera House's status and appeal as an outstanding visual, cultural, and tourist focal point.

The Sydney Opera House is associated with many important professionals, both architects and engineers.

3. Engineering design, innovation and construction

The 'House' comprises the forecourt, the podium; the monumental steps leading up to the podium and box office foyer (with the steps resting on great 49-metre span folded beams over the lower visitor access and vehicular concourse); a concert hall and opera theatre; and within the podium, a playhouse, a studio theatre and ancillary spaces, including offices. 'The complex comprises more than 1000 rooms ...' (World Heritage Nomination).

3.1 The podium and folded beams

Utzon's podium concept was inspired by Mayan temples climbed by worshipers to escape the jungle; at the Opera House, patrons and visitors could climb the steps to rise above the city and enjoy the views.

"The construction of the podium was a significant design and engineering achievement. The challenge was to construct a podium that simultaneously created a sense of the continuation of the natural landscape and a bold modern structure of continuous reinforced concrete that rose out of the ground and overlooked the harbour (Weston

2002: 129). Utzon's initial design concept was for the concourse to be supported by a number of columns. Ove Arup investigated ways to better reflect Utzon's precepts: 'Express honestly the characteristics of the materials used' and 'Let the structure speak for itself' (Murray 2004: 25). The bold solution was a beam that integrated the techniques of folded plate structures and prestressing. The single span design created both a sculptural and efficient form (Murray 2004: 26-27). This design provided the ability long sought by architects to provide huge spaces unencumbered by structural supports. Utzon credited the design as 'Ove's invention' (Murray 2004: 27)”[1].

The Stage 1 contract – for the foundations, podium and steps, was let to Civil & Civic who commenced work on 2 March 1959, with the work being completed in February 1963.
A detailed description of the design of the ‘folded beams’ is at https://www.arup.com/perspectives/publications/the-arup-journal/section/the-arup-journal-1973-issue-3#

3.2 The roofs

3.2.1 Preamble

The problems facing the structural engineers when commencing design of the roofs, are summarised by Ove Arup and Jack Zunz in the following:

> “Utzon conceived the scheme which he submitted for the competition, apparently unaided by structural engineering advice. The distinctive sculptural quality of the building with its roof structure, often likened to billowing sails, was an essential part of his first proposals. On the other hand, the design was extremely sketchy and no more than an indication of the architect's intentions. The shape of the roof was based on an intuitive technical assessment of how to create surfaces with a very strong aesthetic appeal. All surfaces were free shapes without geometric definition and their structural viability had to be proved.
>
> Strictly speaking, Utzon's intuitive technical assessment turned out to be erroneous. He had visualized the roof as thin shells. This was not possible since the very shape of the roof introduced high bending moments regardless of any structural system”[1].
>
> “In structural engineering terms, [amongst other things] … a geometric discipline had to be imposed on the surfaces in a way which would provide adequate clearances for the stage towers, balconies and auditoria roofs, all of which were unknown in any detail, and provide surfaces and silhouettes in accordance with the architect's fundamental concept. The discipline was also needed to predict the spatial position of points on the surfaces for construction purposes”[2].
>
> “The architect welcomed the introduction of a geometric discipline”[3].

To achieve a solution to the roof design it became clear that to cope with the vast quantity of geometric problems and the complexity of the analytical work, extensive use of computers would be required.

- While Utzon welcomed the introduction of a geometric discipline, the design of the roof system took from 1958 to 1962-63, with the geometry undergoing a number of changes involving parabolic, ellipsoid and spherical shapes to preserve the architect's concept, to accommodate stage machinery etc., and to ensure structural integrity. It involved model-testing and analysis using computers of numerous alternatives of roof shapes, materials and structural forms in a lengthy iterative process. As well as the main roof shells, side shells had to be devised and fitted to the sculptural form. 'Some 12 schemes were studied, and the shell solution developed to some finality, before a final structural concept was selected'[4]. (A description of the design of the roof, together with the history of the development of its design is at https://www.arup.com/perspectives/publications/the-arup-journal/section/the-arup-journal-1973-issue-3#).

  'Intensive efforts were made to retain the integrity of the initial design comprising shell roofs that remained self-supporting without reinforcements'... [Eventually], In late 1961, Utzon was struck by the idea that all the roof shapes could be derived from a single sphere'. Sharing a common radius, the segments could be broken into individual components, prefabricated and then assembled on site (Murphy 2004: 6). Utzon acknowledged that all the work of the previous years had contributed to reaching the new 'magnificent solution' (Nobis 2004: 47)[5].

  "... the roof structure consists of over 2400 precast units and more than 4000 tile panels. All precast members were manufactured in a factory established on site ... For the structural components, formwork was generally steel framed with a plywood lining. The plywood was treated with several layers of fibreglass bonded polyester resin to give a smooth and precise finish. All ribs and arch members were manufactured with matching surfaces suitable for a thin 0.8 mm - 3 mm maximum, epoxy resin joint.

  Tile panels were manufactured in concrete moulds on which aluminium strips set out the tile positions and provided the recessed mortar joint the architect had specified ... Differential shrinkage between the tiles and the concrete backing was largely controlled by the stiffening ribs but the curvature of the solid warped surface panels had to be specially adjusted"[6].

  Radiating from the pedestals, the ribs formed a fan when joined together. Consequently, the segments of each rib in the same arc were identical and could be cast in the same mould. This also applied to the tile lids in each arc, thus enabling many reuses of the formwork for each; accordingly, the 'uniform sphere' concept provided significant cost savings in re-use of the formwork, and made erection of the ribs easier.

  The roofs were constructed by joining together with epoxy resin joints a set of concrete arched ribs with the centre line of each rib being a great circle of a sphere having a radius of 75m. The rib segments were pre-cast on the site and stressed together after erection.

3.2.2 Erection arch, erecting the ribs and survey control

To erect the roof Corbet Gore, Hornibrook's construction director conceived a travelling erection arch to support the rib components as they were being placed in position and stressed together; this avoided supporting scaffolding.

“[The erection arch] was brilliant in concept and application ... [It] comprised a steel lattice truss, curved to the same shape as the roof ribs, and had to be able to telescope and twist since the ribs were of varying length and each half lay in a different plane. The design development took 18 months and it was tested prior to installation. Four were used at any one time, and the cost and time savings over alternatives were enormous'[1].

“Rib segments were picked up by a tower crane hooked with a special Hornibrook-invented slinging gear that could swivel the segment in any direction to orientate it to drop it into its position on the shells. That position could be close to horizontal above the side shells or near vertical at the springing point. Segments would then be attached one at a time from pedestal to crown, each one joined with epoxy resin to the one previously placed and held tight by temporary stressing cables, and in position between the previously erected rib and the erection arch. But the erection arch was flexible and could deflect more than three inches. And the ribs were very flexible because they were of thin concrete and very heavily stressed. Also, with a rib the shape of a great circle with a radius of 246 ft, if you rotated it a very small amount, an eighth of an inch on the inside and an eighth of an inch on the outside, then it moved sideways at the top three inches. 'And if it did that (once stressed) it would actually twist itself and snap and fall apart. Gore was only too well aware of this and that a rib segment could kick out under stressing and snap like a green stick, so precision in surveying was imperative”[2].

Precise survey control of construction of the Opera House and especially of the roof, was of critical importance to a successful outcome.

“'To calculate the position of six or eight points on a rib took two weeks with an electric calculator. So, to locate the segments in three dimensions in space in the complex geometrical structure of the shells …’, a three-dimensional program for the geometry of the shells was written.[3] Each segment was given a code number to establish its hall, its shell, its rib and its segment number, and the code was written with a felt pen beside a surveying nail in the segment. The theoretical position in space of the segments was established in the three-dimensional program. Four survey positions were set up in the Botanic Gardens and around the shore of the Harbour so that the moment segments were up, the surveyors could immediately sight them with the segment code number and jot it down on a table. The readings were picked up by cab to feed into the computer program which would run that night at AGE and in the morning the results would come back with the exact elected position of the segment and whether it was half an inch or a quarter of an inch out so it could be adjusted if necessary'.[3]

'The surveying program for the shells was run 900 times during construction'[4].

3.2.3 Epoxy bonding of segments

“[The] innovative epoxy resin process was developed for bonding the segments together, following extensive research by the Cement and

Concrete Association (England) and the University of New South Wales (Australia).

This achieved a smooth concrete effect which was vital for Utzon's design as the concrete surfaces of the shells would remain exposed in many of the building's interiors. The use of epoxy in concrete construction was in its infancy at the time and much research was undertaken to develop a suitable resin with the necessary strength, appearance and weathering characteristics (Murray 2004: 53; Addis 2005)"[1].

"All ribs and arch members were manufactured with matching surfaces suitable for a thin 0.8 mm - 3 mm maximum, epoxy resin joint".[2]

"The chosen treatment for the matching surfaces of the segment ends was to grind the surface to just expose the aggregate not more than 10 days before jointing. Immediately before application contact faces were treated by wiping with dewatered absolute alcohol to dry and clean the surfaces. The resin was applied to both faces. On the lower face it was placed and spread with a spatula or grooved scraper and the upper surface was coated using a paint roller.

These methods proved completely successful on site and sound joints were obtained consistently, provided a precompression was applied to the joint during the setting period"[3].

3.2.4 Tile cladding of the roofs

"The spectacular tiled surface of the shells represents a great architectural triumph and exemplifies Utzon's marriage of craft and technology, tradition and the search for new forms of expression. Utzon believed that the covering for the gigantic, curved forms of the shells would have 'the greatest influence on the visual impact' of the building (Weston 2002: 148)…

The Swedish tile manufacturer Hoganas was commissioned to produce the highly specialised tiles as no standard product was available. Research and experimental work were undertaken to develop a tile that would produce the colour, surface texture and pattern specified by Utzon and meet other technical requirements.

It took three years of experimentation to achieve the right quality and finish: a white transparent glaze and uneven texture for the tiles for the main areas, creating a diffused and softer reflection of the sun than the hard image created by a standard glaze; and a matt, off-white tile for the edges. Hoganas pioneered a special process of coating, firing and glazing that gave the tiles a beautiful lustre or sheen, a surface that would retain its visual qualities even when the tile became dirty (Utzon 2002: 20-22).

A new design solution then had to be devised to successfully bond the tiles to the curved shell structure. Changes to the shell structure meant that the original design to fix the tiles directly to the shells was no longer feasible. A solution was found using 'tile lids' which modified a Swedish process and used an unusual glue process to create a recess between each two tiles in order to define the edges[1] [the lightweight tile lids were constructed of a thin slab of concrete reinforced with wire mesh].

Around 4253 precast large chevron-shaped panels were manufactured and the tiles were bonded diagonally by a machine to produce a perfect uniform surface. Drawing the layout of each individual tile was an enormous feat - there were more than one million tiles and 41 types of edge tile. Ove Arup & Partners prepared 350 detailed drawings for the tile panels alone”[1].

3.2.5 Waterproofing the ribs and tile lids

“The effort and investigations that took place to seal the shells, including the joint between the tile panels, is a story in itself. Utzon's files on the matter extend to 500 pages of correspondence. Arup's double that. Arups alone consulted with 32 companies in Australia and 18 in the UK during their quest. In the December 1963 *Arup Newsletter* Zunz wrote:

> 'Waterproofing this roof is a major problem and in itself is a story of technical and human endeavour'.”[1]

“Arups and Utzon's office embarked on enormous and extensive parallel investigations leaving no stone unturned in a quest to find a way to waterproof the joint between ribs in the Rice Structure to allow for movement”… Arups favoured lead, Utzon preferred copper.

Lead caulking was the ultimate outcome of a bitter struggle and emerged victorious largely because it could permanently resist movement”[2].

3.3 Glass walls

“The design solution for the glass walls pushed the boundaries of contemporary technology to the limit and took eight years to complete. Such a design was unprecedented and Utzon had not completed a design solution prior to his departure. Architects Hall Todd & Littlemore and engineers Ove Arup & Partners devoted much time to the complex design and engineering challenges posed by Utzon's design concept. Extensive research, experimentation and testing were undertaken to resolve the problems which involved calculation of the load-bearing characteristics of the glass; design of a supporting framework that would load the glass to a degree it could withstand; investigation of structural materials for the mullions; and construction and erection of prototypes under the shells. The final solution was a design of planar glazing with minimal external mullions and internal steel structure set back from the glass.

The glass walls were a considerable design and engineering achievement. They were the first large-scale example of the use of glass in a building both as a structural material and as a window and became 'the precursor of a style of enclosure that has now become commonplace' (Murray 2004: 129). The Sydney Opera House was the forerunner of many dramatic glass walls that have been constructed since, notably the glass wall at La Villette in Paris by Peter Rice (who worked for Ove Arup & Partners on the Sydney Opera House) and the engineered glass structures of the eminent German engineers Jorg Schlaich and Werner Sobel (Addis 2005). The walls won Ove Arup & Partners an award for engineering excellence in 1972 from the Association of Consulting Engineers of Australia”[1].

3.4 Computers and the Opera House

3.4.1 Computers - preamble

In March 1969, Ove Arup and Jack Zunz a partner and responsible for the Sydney Opera House project, made the following comment at the Institution of Structural Engineers in London:

> 'With hindsight, it is felt the shells could probably not have been built without the use of computers. We could not have produced the mass of information, let alone the analytical work necessary to erect the building in the time available'[1].

"At the time the Opera House project started engineers were aware of sophisticated analytical methods and derivations from first principles; designers ... used simple formulae, tables and empirical data to assess the performance of structures; there were reference books of design tables; and designers used slide rules as their main calculating engine, and for more precise calculations they used tables of logarithms"[2].

In 1951 the Manchester firm of Ferranti marketed the first commercial computer in the world, the Mark 1, and Ferranti produced the successful Pegasus-1 in 1956[3].

The complexity of the shells forced the design team to look for computational power on a scale never before employed. As design activities got underway the London office of Arup sought access to the most powerful computers. However, they could not produce answers as fast as the engineers wanted, nor was there the software to do it, so the Opera House team had to create software programs from scratch[4].

In addition to the computers in London, Arup worked with Southampton University and gained access to its Pegasus computer for lengthy calculations, wind tunnel and structural model tests from 1958 until 1961[5].

"The method of analysis relied very heavily on the use of electronic computers. It is difficult to visualize how the necessary calculations could have been made without them. It must be remembered that this was one of the first large-scale applications of electronic computers to a building structure and was made at a time when the capacity and speed of the machines, the number of available programs and the sophistication of the languages, were very much less than they are now. Perhaps more important, there was not at the beginning anyway, a complete understanding among practical engineers of which analytical approaches were best suited to the machines' capabilities"[6].

(The use of computers on the Opera House closely followed that in 1956 for the tender design and final design of Sydney's Gladesville Bridge, by Anthony Gee. Gee was a 22 year old Cambridge graduate working in G Maunsell & Partners' London office - both he and Arups used the same Pegasus computer. The Pegasus and a printout were on display at the Victoria & Albert Museum's exhibition: *Engineering the World: Ove Arup and the Philosophy of Total Design*, that ran from 18 June to 6 November 2016 - Appendix C).

3.4.2 Computers and the folded beams

"An integral part of the foundations was the concourse within which the main supporting structure was an array of folded beams, beams which had a kink along their length"[1]. These beams were analysed by a series of iterative calculations, processed by the Pegasus computer.

"The original computer used by Arup took 12 to 14 hours to complete a sequence of structural analyses, a process that would take less than a minute on a modern personal computer" [in 2006][2].

"Whenever the design changed an immense amount of work had to be scrapped. Software was modified as ideas evolved and new software was written to tackle the final form of the shells"[3].

3.4.3 Computers and the roofs

"All main shells had to be analysed in both the simply-connected and the laterally stressed conditions… The largest framework had 136 joints (about 780 equations) and took nearly four hours machine time for five load cases. The calculation and preparation of the input data for this shell took approximately three weeks"[1].

"For the final analysis each side-shell structure was simulated by a rigid three-dimensional space framework of straight prismatic members. This was analysed on a Ferranti Pegasus Computer using a general space framework program based on the stiffness method. This framework program had been written in machine-code by Dr A. Baker, one of the engineers working on the project. The program, as originally written, was limited to structures with 18 or fewer joints, but was later extended by a partitioning device to cope with larger structures"[2].

Hornibrooks designed the erection arch in-house ... using self-written computer programs. "The only machine capable of dealing with the data was the IBM 7090 located at the Weapons Research Establishment (WRE) at Salisbury in South Australia. Evans had to travel from Sydney and spend a week at a time at WRE working night shift, the only time available for the job. He would input his data and program using a stack of punched cards and return to Sydney with the results - a pile of paper an inch (3cm) thick. If the results did not make sense he would make the necessary adjustments, go back and run the data again"[3].

Hornibrooks also used the Australian General Electric Company's computer in York Street, Sydney for position-checking during erection of the arch ribs – refer to 3.2.2.

3.4.4 Computers and the glass walls

"As the Opera House took shape, attention turned to the glass facade infills to the shells…

The spherical geometry of the shells and podium dictated a geometry based on cylinders and cones for the glass walls. It remained to relate all these surfaces mathematically so that calculations could be done for every intersection point. Thus, the length of every supporting member, the angle of cut at its ends, the position of the bolts, the shape of each connection to the shell rib, the size and shape of every sheet of glass, together with the forces on them, could be calculated. Small changes in requirements meant the entire program being run through the computer again"[1].

3.4.5 Additional computer applications

As well as the application of electronic computers with respect to the structural analysis ... "Extensive use of computers was also made in other ways. So much geometric information for all parts of the structure and its cladding was needed that it could sensibly be provided only by the computer. This geometric information was required for three purposes - for design, for drawing three-dimensional shapes and for setting out on site. The computer helped to minimize the possibility of errors, as well as to save time, and was programmed to give information tabulated either to suit rapid conversion into drawings or to suit being fed to the craftsmen on site, who set out some of the works directly from the computer print-out.

The contractor made use of the computer for the design of the erection arch, statistical control of concrete strengths and job costs; interpretation of the latter sometimes led to design changes in order to achieve economy. Wages were also handled by the computer"[1].

In the Concert Hall and Opera Theatre, computers were used for scheduling the precise dimensions of the plywood ceiling panels. Hornibrook caused some excitement at IBM, as their software was too big for the computers in Sydney to cope with, so certain programs had to be run on the larger Weapons Research computer in Adelaide[2].

"Use of computer technology was not just confined to the Opera House structure. The acoustics also benefited from software used for the calculation of reverberation time and geometric constructions of reflections …

Computer software also played a part in the design of the loudspeaker columns. Each column had 19 speakers, the first of their kind in the world …

The stage lighting systems in the completed Opera House are elaborate. A computer system recorded the intensity settings of up to 200 different controls …

The Opera House complex housed an amazing network of electrical equipment, probably the most advanced of any performing art centre in the world at the time. A 'room service' module was installed in the dressing rooms of star performers and the offices of key staff. To tune an instrument, for example, there was no need to use a tuning fork. The module gave the artist the very sound required with all the overtones the normal instrument produces …

The Sydney Opera House experience enthused the building industry professions and more of them experimented with computers. By the late 1960s Arup had contributed to formulating the plans for computer application development in the European Community. Arup was also a founding member of CICA, still the UK's construction computer users' group. Australia formed a similar group called ACADS. Between them they established the international alliance FACE, bringing in the United States, Japan, and other European countries"[3].

3.5 Summary of technological innovation

In concluding his essay *Constructing a legacy: technological innovation and achievements,* Dr John Nutt summarised the technological innovation and achievements as follows:

"The Sydney Opera House comprised many technological innovations which pointed the way to the introduction of computer design and analysis, and the mathematics associated with computer drafting. It was undoubtedly the first computer-designed building of significant scale which could not have been built without the use of computers. The design was innovative and of great complexity. None of the traditional details of building or bridge construction worked, and all, from small waterproofing details to large-scale erection, had to be researched and developed from first principles. It was the first example of factory manufacture and erection of large precast concrete units based upon such complex geometry, and the pre-calculation of all dimensions right down to the positions of the last bolt and hole on such a scale was unique. Epoxy jointing of matched concrete segments was the earliest example of its type in the world and certainly the largest for many years. These methods have since found their way into accepted bridge and structural engineering practice. Many of the prestressing details were innovative, and the development of cement grout based on investigations using radioactive trace elements pioneered their widespread use in the building industry. The erection arch designed by the builders, which was capable of telescoping and rotating into a large number of different positions, is certainly the most complex piece of scaffolding used in the bridge, building and construction industry in Australia. Finally, it was the first large-scale use of walls and roofs with laminated glass.

Utzon's architectural vision, which became reality, was matched by the quality of the technology and the creativity of the Arup engineers. Their dedication to supporting his architectural philosophy is demonstrated in every detail. It is a magnificent tribute to the collaboration of architect and engineer, to art and technology"[1].

4. Assessment of significance

Historical significance

The Sydney Opera House is historically significant as an architectural masterpiece, made possible by brilliant engineering innovation, design and construction; it is recognised internationally as a symbol of Sydney and Australia.

Historic Individuals

Architect Jørn Utzon's Sydney Opera House is significant for its association with him and with many other professionals, particularly engineers Ove Arup, Jack Zunz and John Nutt of Ove Arup & Partners, and Corbet Gore, Construction Director of the Hornibrook Group, and with surveyor Michael Elphick.

Creative or Technical Achievement

"The Sydney Opera House comprised many technological innovations which pointed the way to the introduction of computer design and analysis, and the mathematics associated with computer drafting. It was ... the first computer-designed building of significant scale which could not have been built without the use of computers. The design was innovative and of great complexity. None of the traditional details of building or bridge construction worked, and all, from small waterproofing details to large-scale erection, had to be researched and developed from first principles. It was the first example of factory manufacture and erection of large precast concrete units based upon such complex geometry, and the pre-calculation of all dimensions right down to the positions of the last bolt and hole on such a scale was unique. Epoxy jointing of matched concrete segments was the earliest example of its type in the world and certainly the largest for many years. These methods have since found their

way into accepted bridge and structural engineering practice. Many of the prestressing details were innovative, and the development of cement grout based on investigations using radioactive trace elements pioneered their widespread use in the building industry. The erection arch designed by the builders, which was capable of telescoping and rotating into a large number of different positions, is certainly the most complex piece of scaffolding used in the bridge, building and construction industry in Australia. Finally, it was the first large-scale use of walls and roofs with laminated glass.

Utzon's architectural vision, which became reality, was matched by the quality of the technology and the creativity of the Arup engineers. Their dedication to supporting his architectural philosophy is demonstrated in every detail. It is a magnificent tribute to the collaboration of architect and engineer, to art and technology"[1].

Aesthetic significance
The structural engineering of the Sydney Opera House is of exceptional aesthetic significance through its culmination in beautiful geometric forms that have a sculptural quality; the great folded beams that carry the concourse, the roof ribs with their pedestals, the tile lids, and the glass walls, are an essential part of the visual appeal of the House.

Social significance
As evidence of the engineering which produced the sculptural form of the Sydney Opera House, the visible structural elements attract visitors, and are a major contributor to the House's status as an internationally recognised symbol of Sydney, one of Australia's leading tourist attractions and a focal point for community events.

Research potential
The structural engineering of the Sydney Opera House which involved one of the first large-scale applications of electronic computers in design of a major building structure, and pushed engineering and building technology to the limit, is significant for its research potential in respect of:

- design of the roofs;
- design of the great folded beams;
- design of glass walls;
- use of epoxies for jointing matched concrete segments;
- waterproofing of the roof ribs; and
- survey control.

Rarity
The roof rib structures, their pedestals and the great folded beams under the monumental steps are rare. 'The glass walls were a considerable design and engineering achievement. They were the first large-scale example of the use of glass in a building both as a structural material and as a window and became the precursor of a style of enclosure that has now become commonplace' (Murray 2004: 129)[2].

Integrity/intactness
The structural elements of Sydney Opera House have great physical integrity and intactness.

5. Comparative analysis

5.1 Comparable or similar projects in this and other countries.

“Since its opening [nearly five decades ago], the Sydney Opera House has attracted widespread and intense commentary, discussion and analysis across a number of professional disciplines and in popular culture. Architects, engineers, cultural theorists and architectural historians have dissected the building and assessed Jørn Utzon's contribution to the history and development of modern architecture. As with the history of the Sydney Opera House, this outpouring has been marked by energy, enthusiasm and debate; yet there is overall agreement that the Sydney Opera House is one of the great buildings of the 20th century.

The Sydney Opera House is unique for its diverse and outstanding architectural and cultural heritage values as a masterpiece of modern architecture, as an internationally famous icon, and for its great engineering feats and technological achievements. It is outstanding for the unique composition of all these features. Architectural historian Richard Weston has described the Sydney Opera House as 'the most recognisable contemporary man-made structure in the world' which is, quite simply, one of a kind (Weston 2004b). The image and tectonic integrity of the Sydney Opera House are powerful, original and unrepeatable (Frampton 2004; 21).

The Sydney Opera House can be compared with other masterpieces around the world on the basis of architectural excellence and outstanding engineering achievement.

5.2 Masterpieces of structural engineering and technology that stretched the boundaries of the possible

Tombesi has compared the Sydney Opera House to a number of exceptional buildings dating from early times to the present that all share the same outstanding characteristics of architectural, engineering and construction innovation (Tombesi 2005). Two buildings with similar types of materials and structure that are particularly noteworthy include Pier Luigi Nervi's Exhibition Buildings at Turin (Italy 1948-1949) and Eero Saarinen's TWA Terminal Building at Kennedy Airport in New York (United States 1956-1962) (Tombesi 2005). These buildings, along with the Sydney Opera House, pushed the boundaries of the reinforced shell typology to new limits, realising the vision of the 'first generation' architects for reinforced concrete.

Nervi's Exhibition Buildings are internationally recognised as 'masterpieces of logical structure and sculptural precision' (Richards 1977: 228). Nervi stated that the thin prefabricated concrete roofs of the buildings at Turin 'would have been impossible without a simultaneous invention of the structural method' (Joedicke 1989: vii). He set out to interpret and command the 'mysterious laws of nature' and thereby to express their 'majestic eternity' (Jencks 1973: 73). The work of Nervi is visually characterised by the tapering or modelling of concrete beams and columns to reflect the complex structural forces within. Nervi's designs were driven by structural integrity and his engineering combined clear logic with remarkable aesthetic sensitivity. Like Nervi, Utzon was also inspired by the laws of nature—'my laboratory is the beach, the forest, the sea and the seashore' (Weston 2002: 278). But in abiding by these laws, Utzon found room for a poetry and lyricism that is missing in some of Nervi's Exhibition Buildings. Utzon and engineer Ove Arup matched Nervi's innovations with quantum leaps in engineering science, the design and erection of prestressed concrete and the precision of precasting

and formworking made possible through an innovative use of new computer technologies.

In comparing the Sydney Opera House with Saarinen's TWA Terminal it is clear that the buildings share some common origins in terms of the combinations of architectonics and structural engineering and similarity of roof shapes. Both represented outstanding architectural design and engineering achievements. Saarinen took in-situ concrete construction to its practical limit in the TWA Terminal, using the curvature of the thin roof covering to provide both span and rigidity.

The Sydney Opera House bears important similarities to the buildings of Nervi and Saarinen. It is a dramatically strong work in terms of its siting within the landscape, its structural design and construction and its complex architectural meaning even in comparison to the buildings of Nervi and Saarinen discussed above. All the buildings share amazing technological feats in the use of large clear spans and the extensive use of concrete. But the functional simplicity of the Nervi and Saarinen roofs serves to highlight the complex structural and architectural expression of the roofs of the Sydney Opera House".

Source: *Sydney Opera House: Nomination by the Government of Australia for Inscription on the World Heritage List 2006*

6. Recommendation

It is recommended that the engineering achievements and technological innovation in the design and construction of the Sydney Opera House, be awarded an Engineering Heritage International Marker.

Image: Michael Clarke

7. Interpretation

In her letter of support, the Chief Executive Officer of the Sydney Opera House has advised that support for the nomination 'is on the basis that, if successful, a non-physical digital plaque would be provided to the [Opera House] Trust. Installation of a physical metal plaque cannot be supported as this would be considered intrusive under the Opera House's Conservation Management Plan'.

Accordingly, following approval to this nomination, a digital plaque will be prepared in consultation with the Opera House management.

8. Endnotes

1. Introduction

1. *World Heritage Nomination*, p. 13
2. Ibid
3. https://www.sydneyoperahouse.com/our-story/sydney-opera-house-history.html
4. *The Sydney Opera House,* Arup and Zunz
5. *The forgotten hero*, Baume, Spectator Australia, 2 November 2013
6. *Building a masterpiece*, p. 108
7. *The Sydney Opera House* - Arup and Zunz
8. *The forgotten hero*, Baume, Spectator Australia, 2 November 2013

3. Engineering design, innovation and construction

3.1 The podium

1. *World Heritage Nomination*, p. 37
2. *The Sydney Opera House*, Arup & Zunz, pp. 6-7.

3.2.1 Preamble

1. *The Sydney Opera House* - Arup and Zunz, p. 5
2. *The Sydney Opera House* - Arup and Zunz, p. 8
3. Ibid
4. *Building a masterpiece*, p. 111
5. *World Heritage Nomination*, p. 38
6. *The Sydney Opera House* - Arup and Zunz, p. 14

3.2.2 Erection arch, erecting the ribs and survey control

1. *Building a masterpiece,* pp. 117
2. Opera House Act One, p. 362
3. Ibid
4. Opera House Act One, p. 363

3.2.3 Epoxy bonding of segments

1. World Heritage Nomination, p. 40
2. *The Sydney Opera House* - Arup and Zunz, p. 14
3. *The Sydney Opera House* - Arup and Zunz, p. 19

3.2.4 Tile cladding of the roofs

1. *World Heritage Nomination*, pp. 41 & 42

3.2.5 Waterproofing the ribs

1. Opera House Act One p. 508.
2. Opera House Act One p. 339.

3.3 Glass walls

1. *World heritage Nomination*, p. 40

3.4 Computers and the Opera House

3.4.1 Preamble

1. *Building a masterpiece*, p. 85
2. *Building a masterpiece*, p. 86
3. Ibid
4. Ibid
5. *Building a masterpiece*, p. 89
6. *The Sydney Opera House*, Arup & Zunz, p. 17

3.4.2 The folded beams

1. *Building a masterpiece*, p. 89
2. *Building a masterpiece*, p. 91
3. *Building a masterpiece*, p. 92

3.4.3 The roofs

1. *The Sydney Opera House*, Arup & Zunz, p. 18
2. *The Sydney Opera House*, Arup & Zunz, pp. 17 & 18
3. *Building a masterpiece*, p. 102

3.4.4 The glass walls

1. *Building a masterpiece*, p. 97-98

3.4.5 Additional computer applications

1. *The Sydney Opera House* - Arup and Zunz, p. 19
2. *Building a masterpiece*, p. 97
3. *Building a masterpiece*, pp. 100-101

3.5 Summary of technological innovation

1. *Building a masterpiece*, p. 121

4. Assessment of significance

1. *Building a masterpiece*, p. 121
2. *World heritage Nomination*, p. 40

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- *Sydney Opera House: Nomination by the Government of Australia for inscription on the World Heritage List 2006*
  Ove Arup and Jack Zunz: *Sydney Opera House.* (The Arup Journal, 3 October 1973), https://www.arup.com/perspectives/publications/the-arup-journal/section/the-arup-journal-1973-issue-3#.
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  https://www.sydneyoperahouse.com/our-story/sydney-opera-house-history.html

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11. Appendices

A: Sydney Opera House Timeline.

B: Tony Gee on the use of computers in the design of Sydney Opera House and of Gladesville Bridge.

C: Selected prominent engineering and technical people associated with design and construction of the Opera House.

D: Sydney Opera House – a Conservation Management Plan: Statement of Significance

Appendix A

Sydney Opera House Timeline

1947

- Eugene Goossens, conductor of the Sydney Symphony Orchestra calls for "a musical centre housing a big hall for a symphony orchestra, a small hall for chamber music and a fine home for an opera company".

1952

- J. J. Cahill becomes Premier of New South Wales.

1954

- J. J. Cahill convenes conference to discuss 'the establishment of an opera house in Sydney', 30 November; formation of Opera House Committee.

1955

- Premier Cahill announces that Bennelong Point [presently a tram depot] is to be the site for the new opera house, 17 May; and that the Government will hold an international competition for the design of "an opera house", 13 September.

1956

- Release of program and guidelines for an 'International competition for a national opera house at Bennelong Point, Sydney ...' February.
- Eugene Goossens departs Sydney after being charged with bringing prohibited material into the country, March.
- Melbourne Olympic Games, November.
- Opera house competition closes, 3 December.

1957

- Scheme number 218 by Jørn Utzon is announced the winning entry by Premier Cahill at the Art Gallery of NSW, 29 January. It is estimated to cost 3.5 million pounds.
- Utzon meets with competition judges Eero Saarinen and Leslie Martin, and engineer Ove Arup in London, February.
- Ove Arup & Partners appointed consulting structural engineer, mid 1957.
- Utzon's first trip to Sydney, 29 July - 22 August; first model displayed at Town Hall in conjunction with launch of funds appeal.

1958

- Utzon and Arup visit Sydney, March-April; Utzon presents 'Sydney National Opera House' report, known as the 'Red Book'. Demolition of tram sheds on Bennelong Point, August.
- Foundation stone laid by Premier Cahill
- Demolition of the Bennelong Point Tram Depot commences, August.
- Ove Arup formally engaged as structural engineers for the project, November.

1959

- Civil & Civic Contractors Pty Ltd awarded contract for foundations and podium – Stage 1, January.
- Utzon attends plaque-laying ceremony to celebrate the commencement of Stage 1, 2 March.
- Death of J. J. Cahill, 22 October.
- Premier R. J. Heffron opens Ralph Symonds new plywood factory at Homebush Bay.

1960

- Arup engineers in London continue extensive structural analysis of the shells — ellipsoid roof design replaces parabolic scheme.
- Paul Robeson sings for the workers on site, 9 November.
- Ralph Symonds drowns at Palm Beach, 1 January.
- Utzon purchases land at Bayview, Sydney.
- Formation of Sydney Opera House Trust, March.
- Extensive testing of tiles continues at the Hoganäs factory, Sweden.
- Utzon develops spherical scheme as final solution for shell design, September.

1961

- The Sydney Opera House Trust established.
- Jack Zunz, a partner in Arups takes over responsibility for the Opera House project from Ronald Jenkins.
- Utzon and Ove Arup & Partners achieve the 'spherical solution' for the roof shells after three years of concept development.

1962

- Utzon submits second presentation report, the 'Yellow Book', January.
- Utzon and Arup's Jack Zunz present new spherical scheme in Sydney, March
- M. R. Hornibrook (NSW) Pty Ltd appointed as contractor for Stages 2 and 3, (the roofs and interior) on a 'cost plus fixed fee' basis.
- New estimates put cost of Opera House at 13.75 million pounds, April.
- Utzon's experimental black-ribbed scheme for the shells stirs up media controversy, June.

1963

- The foundations and construction of the podium (Stage 1) completed, February.
- Utzon and his family relocate to Sydney; new contractors M. R. Hornibrook begin work on the construction of the shells (Stage 2); production of tiles begins at Hogänas, March.
- In conjunction with the acoustics consultants Utzon and his office work on seating and plywood ceilings for the two auditoria.
- Commencement of erection of first pre-cast rib vault, November.

1964

- Utzon wins Zurich State Theatre competition, May. Focus of design activity moves from Bennelong Point to Utzon's second office at Palm Beach, November.
- Two 1:96 scale models completed by Finecraft, Sydney, the second a sectional model. showing Utzon's scheme for the red and gold plywood interior of the Major (Concert) Hall, October to December.
  Utzon's plans for his house at Bayview rejected by Warringah Council.

1965

- A newly elected [conservative] government takes office with an agenda to limit the construction cost and time overruns.
- New cost estimates of 24.7 million pounds and completion date of 1969 announced by Davis Hughes, Minister for Public Works, August.
- Utzon's requests for funding for construction of plywood mock-ups for Stage 3 not met.
- Utzon makes repeated claims to Davis Hughes for fees owing to him.
- Continuing deterioration of relations between Utzon and Arup engineers over plywood ceilings.

1966

- Utzon submits letter of withdrawal to Davis Hughes, 28 February.
- Architect Harry Seidler, author Patrick White and others lead march protesting at Utzon’s treatment, 3 March.
- Utzon rejects Hughes' proposed subsidiary role for him under the Government Architect; Utzon-in-Charge committee organises.
- Town Hall rally, 14 March.
- Special meeting of the Royal Australian Institute of Architects under presidency of Ron Gilling fails to provide necessary support for Utzon, 28 March.
- Hall, Todd & Littlemore appointed by Hughes and Government Architect to replace Utzon, 19 April.
- Utzon and family leave Sydney, 28 April.
- The Government pays Utzon's representatives $160,000 in return for 130
- architectural drawings for Stage 3, 17 May.
- Hall, Todd and Littlemore submit "Review of Program" and suggest major changes to the use of halls, 12 December.

1967

- Installation of last (2,194th) precast shell segment on 17 January effectively marks the completion of Stage 2.
- Stage 3: construction of the glass walls and interiors commences.
- On the first anniversary of his withdrawal Utzon asks Davis Hughes to reinstate him, 28 February.
- Conflicting requirements of seating, acoustics and stage machinery for the major hall result in announcement that it will now be a single-purpose concert space with opera in the minor hall, March.
- Installation of tile lids proceeds.

1968

- In a recording played at a packed Town Hall rally, Utzon again indicates his willingness to return, 19 February.
- With the re-election of Davis Hughes in the NSW State elections Utzon finally concedes defeat, 24 February.
- Hughes announces Opera House will now cost $85 million and open in 1972.

1973

- Responsibility for the Opera House is given to the Sydney Opera Trust and the
- Minister of Cultural Activities.
- Construction of the glass walls and interiors (Stage 3), completed.
- First concert in Concert Hall, 29 September.
- Opening of Opera House by Queen Elizabeth II, 20 October.
- Utzon is awarded Gold Medal of Royal Australian Institute of Architects.

1974

- The final cost of the Opera House is $102 million (excluding cost for the organ and car park).

1979

- Organ installed in Concert Hall, 30 May.

1975

- Architects' Certificate of Completion, 31 May.

1986-1988

- The land approach and forecourt are reconstructed, and the lower concourse developed.

1988

- Ove Arup dies, 5 February.
- *Building of the century* exhibition opens, Sydney Opera House, 3 June.
- *Unseen Utzon* exhibition opens, Sydney Opera House, 1 November.

1993

- **A car park for 1,100 cars is built under the Royal Botanic Gardens.**

1995

- Utzon’s successor Peter hall dies, 19 May.
- Premiere of ‘The Eighth Wonder’, an opera exploring the story of the Opera House, 14 October.

1997

- First submission for world Heritage listing of Opera House is rejected by Federal Government.

1999

- Utzon is re-engaged as design consultant on the Opera House upgrade program working from Denmark through his son Jan and Sydney architect Richard Johnson, August.

2002

- Release of Sydney Opera House 'Venue improvement plan' and 'Utzon design principles' as a permanent reference for the long-term management and conservation of the 'House', May.

2003

- Utzon awarded prestigious Pritzker Prize, April.
- 3 December 2003: Sydney Opera House is listed on the NSW State Heritage Register.

2005

- 12 July 2005: The Sydney Opera House is included in the Australian Government's National Heritage List.

2006

- Submission of joint nomination by Federal and NSW state governments for inscription of the Opera House on World Heritage List, January.

2007

- 28 June 2007: Sydney Opera House is inscribed on UNESCO's World Heritage List in recognition of its Outstanding Universal Value

2009

- First major upgrade with refurbishing the western foyer - designed by Utzon and son Jan, improved ticketing, toilet and cloaking facilities.

2015

- An underground loading dock completed.

2020

- Beginning in February, multi-million-dollar renewal works will transform the Concert Hall by improving acoustics, stage and backstage areas, theatre systems and accessibility in and around the venue.

Sources:

- *Building a masterpiece: the Sydney Opera House*, Powerhouse Publishing
- *Archives in Brief, The Sydney Opera House*, State Records.
- *The Sydney Opera House*, paper by Ove Arup and Jack Zunz, the Structural Engineer, March 1969
- *Sydney Opera House: Nomination by the Government of Australia for inscription on the World Heritage List 2006*

Appendix B

Computers: their use in the design of Sydney Opera House and Gladesville Bridge

Tony Gee: Email to Vince Taranto, Roads & Maritime Services, NSW

From: Tony Gee
Sent: Saturday, 3 May 2014 3:13 AM
To: TARANTO Vince E
Subject: Re: The Ferranti Pegasus computer...

Vince,
I am very pleased you are interested in the use of a computer in the design of Gladesville because it is perhaps the aspect of the project of which I am most proud. When I refer to this in the company of American engineers, they just don't believe it: because of what came later (IBM, Hewlett Packard, Dell, etc.) they tend to assume that they must have been the the first in everything to do with computers but the fact remains that the first recorded use of a computer in bridge design in USA is 1965. So the DMR was right up-to-date if they had an IBM in 1962. What did they use it for? Did they have to write their own programs?

I am speaking entirely from memory so there may be some slight errors in the dates which follow but I don't think they are too far from being accurate.

There were a number of experimental computers at various academic institutions in the UK in the 50's but the first commercially viable one was the Atlas installed at Manchester University in about 1954. Ferranti was based in Trafford Park in Manchester so the Atlas was in all probability a joint development. The general public could make use of the Atlas but you had to send in your program and input data and they mailed the output back to you. It was not particularly expensive but it quickly became so if you had a few errors in your program initially because you did not have the opportunity to de-bug it. The first open-access computers, which came in about 1956, were the Sirius at Ferranti's bureau in Manchester and the Pegasus at their bureau in Portland Place in London.

It was great fun to use the Pegasus. It consisted of a fair-sized room full of diodes and despite the best air-conditioning they could find - the UK has never been great at a/c - it would regularly overheat and shut down on summer days. You simply called up and booked a time-slot, which meant you had to know how long your program would take - not always easy in those days. If you underestimated, they threw you off when your time expired (if there was anyone else waiting to use it) and if you overestimated you didn't get a rebate for the unused time. It used punched paper tape for all input and output so you had to go along in advance and prepare your program and data tapes. In order to minimize errors, you prepared twin tapes of each and ran them through a comparator machine. This identified

any differences between the two tapes, on the basis that you were unlikely to make the same mistake on both tapes. This worked extremely well and once you had resolved the differences between the two tapes, I don't remember ever having any abortive runs. There was nobody there to help you: you were given an instruction sheet which basically said: "1) Press the ON switch to the on position, etc." I guess the machine was virtually indestructible and there was nothing you could do to harm it.

Development of engineering software, at least in the UK, lagged behind the hardware. As late as the mid-60's, when I was with Atkins, we had a Computing Department to write programs for the other Departments (although I usually found it quicker to write my own!). I don't really know when the first commercial programs became available but I do know that it was the mid-80's before one could buy a reliable program for the design of post-tensioned continuous or balanced cantilever bridges which took proper account of time-dependent effects.

Incidentally, where did you come across the reference to the Pegasus? Did you manage to dig out my articles in *Civil Engineering and Public Works Review?*

Kind regards,
Tony

Tony Gee: Email to Victoria & Albert Museum refuting its claim that the use of computers on the Sydney Opera House project marks the first-ever time computers were used on a large-scale construction project.

From: Anthony Gee [mailto:tonygee@tonygee.net]
Sent: Friday, 21 October 2016 4:16 AM
To: z.trafaswhite

Cc: TARANTO Vince E
Subject: Computers and the Sydney Opera House

Zofia, *(curator of the Engineering the World: Ove Arup and the Philosophy of Total Design Exhibition, at the Victoria & Albert Museum).*
My attention was drawn recently to the web site describing your "Engineering the World: Ove Arup and the Philosophy of Total Design" Exhibition and in particular to the section on "Computers and the Sydney Opera House".

In this section you state: "Arup's pioneering application of computers on the Sydney Opera project pushed the limits of contemporary technology and revolutionized engineering practice" and: "The use of the Pegasus on the Sydney Opera House marks the first ever time computers were used on a large-scale construction project – a game-changing moment in the history of architecture and engineering in the 20th century".

I am afraid I have to correct you: a computer had already been extensively used in the design of a large-scale construction project which predated the Opera House. It is not a coincidence that it was the same computer because, as you say, the Pegasus at the Ferranti Bureau was the only computer in London available for public access at the time. What is a remarkable

coincidence is that the project for the design of which it was used was also located in Sydney, Australia. The Gladesville Bridge was the first 1,000 ft span concrete bridge in the world, a distinction it held for 11 years and one which certainly qualifies it as a large-scale construction project. As you noted with regard to the Opera House, there were no commercially available computer programmes so that original programmes had to be specially written for the purpose. These programmes are described in two articles which appeared in the journal “Civil Engineering and Public Works Review” in December 1960 and January 1961, and clearly show the extent to which the computer was widely used for not only the structural analysis but also the detailing of the bridge.

Tenders were submitted for the construction of the bridge in October 1957. The winning bid was based on an alternative submitted by the contractor for a 910 ft span concrete arch, the design of which had been carried out in the later part of 1956 and the early part of 1957. Subsequently, the span of the bridge was increased to the magic number of 1,000 ft and the redesign was completed by the end of 1958. It was subject to rigorous independent checking and construction eventually commenced in November, 1959. It was completed in 1964 and the bridge was formally opened on 2 October 1964. It is important to note that in the case of Gladesville, the design was totally complete and checked before any construction commenced whereas with the Opera House, construction started long before - many years before, in fact - the design was complete.

The comparative timelines for the two projects are therefore as follows:

	Gladesville Bridge	Opera House
Design started	1956	1957
Design complete	1957	1969
Redesign complete	1958	
Construction started	1959	1959
Construction complete	1964	1973
Official opening	2/10/1964	20/10/1973

I think it is fair to say that in all respects Gladesville predated the Opera House and that the accolades you have attributed to the latter above should rightly be awarded to the Gladesville Bridge.

It is also worthy of note that following its 50th Anniversary in 2014, Gladesville was recognized in 2015 as an “International Historic Civil Engineering Landmark”, a distinction which will no doubt be gained by the Opera House sometime after 2023.

With kind regards,
Tony Gee

Comment:
The exhibition at the Victoria & Albert Museum ran from ran from 18 June to 6 November 2016.
The web page https://www.vam.ac.uk/articles/computers-and-the-sydney-opera-house has since been modified.

Appendix C

Selected prominent engineering and technical people associated with design and construction of the Sydney Opera House.

Ove Arup (1895-1988)

Ove Nyquist Arup (Figure 10.2) was born in 1895 at Newcastle-upon-Tyne, England. His mother was Norwegian and his Danish father served for some time as the Danish Government's veterinary officer to the United Kingdom. Ove Arup attended schools in Germany and Denmark before studying philosophy and mathematics at the University of Copenhagen where he graduated in 1916. From 1916-1922 he studied civil engineering at the Royal Technical College, Copenhagen.

Arup started work as a designer for the Danish civil engineering designers and contractors Christiani & Nielsen in 1922 in their office in Hamburg, Germany. He moved to London in 1923 and became Christiani & Nielsen's chief designer in 1925. While his main activities were civil engineering (mainly marine structures) he became increasingly interested in architecture and the Modern Movement. He became friends with several leading architectural figures, joined the Architectural Association and became active in the Modern Architecture Research Society, known as the MARS Group. In 1933 Tecton (an architectural firm led by Berthold Lubetkin) invited Arup to work on Highpoint 1, an apartment block in London. Arup proposed the use of reinforced concrete (not generally used for multi-storey construction at that time) and a simplified construction method using movable, reusable formwork. When Christiani & Nielsen decided not to proceed with the Highpoint project, Arup moved to Danish firm J L Kier & Co as director and chief designer on the condition that they take over the project. Highpoint 1 came to symbolise some of the tenets of the Modern Movement. Arup worked with Lubetkin on a number of other landmark projects including the much admired Penguin Pool at the London Zoo.

In 1938 Ove Arup founded two civil engineering companies with his cousin Arne Arup: Arup & Arup Ltd and Arup Designs Ltd. He resigned from Arup & Arup in 1946 to establish an independent engineering consultancy with offices in London and Dublin. For a short period, he retained the right to the registered name Arup Designs Ltd. In 1948 he took in three partners to found the practice of Ove Arup & Partners. By the mid-1950s Ove Arup & Partners was established and growing with a client base that included many of the major architectural practices in the British Isles. The firm had a particular interest in modern architecture. Its core activity was to pioneer advanced and economical solutions to buildings, particularly their structures.

A key project was the Rubber Factory at Brynmawr, Wales (with the Architects Co-Partnership) that attracted world attention, especially for its ingenious roof of nine shallow, long-span reinforced concrete shells. Arup's credo of multidisciplinary collaboration found expression in the firm's acquisition and development of all the skills necessary for the design of buildings and civil engineering works.

In 1957, Arup's firm was appointed as the consulting engineers for the Sydney Opera House project. This led to a nine-year partnership between Utzon and Ove Arup & Partners that

was to result in pioneering solutions to the many structural and architectural challenges of the project. The most remarkable aspect of this collaboration was the building of the iconic roof structure. Between 1958 and 1962 Arup, his partners and staff collaborated intensively with Utzon in Denmark and London and developed a number of geometric shapes which resulted in a simplified spherical geometry. This introduced the possibility for repetition in the manufacture of the precast elements for the roof. Ove Arup & Partners also made extensive use of computers in the technical work associated with the design of the project. It was one of the first applications of digital technology to building. After Utzon's departure in 1966 the firm worked with his successors Hall, Todd & Littlemore until completion of the Sydney Opera House in 1973.

The firm Arup founded continued to flourish in the 1970s and 1980s. Offices were opened in Australia —first in Sydney to work on the Sydney Opera House and subsequently in other cities—also in Singapore, Malaysia, the United States, France and latterly in many other countries. Ove Arup & Partners' development was founded on sound technical and social principles. The quest for technical excellence was underpinned by sophisticated information systems and a leading edge research and development group. It was further enhanced by the establishment of specialist services such as information technology; acoustics; economics; urban planning; and facade, fire and seismic engineering. Ove Arup wanted always to marry the highest ideals of design and construction. His background in both the humanities and engineering contributed to his ability to articulate this ideal which he described as 'Total Architecture'. In his own words: 'Good design must first of all satisfy a social function, it must have artistic wholeness and the result must harmonise with its surroundings.' Arup's social principles for his firm have become known as his 'Key Speech' and have continued to operate as the guidelines for the firm.

Ove Arup was made a Commander of the British Empire in 1953 and a Knight Bachelor in 1971. He was elected as a member of the British Royal Academy in 1986 and also received several honorary doctorates. Many of his partners and colleagues have also been honoured and received praise, including Peter Rice who played a leading role in the Sydney Opera House project. Peter Rice was awarded the Royal Institute of British Architects' Gold Medal for Architecture in 1992.

Ove Arup died in London in 1988, aged 92.

Awards presented to Ove Arup include:

- Chevalier First Class (1965) and Commander First Class (1975) of the Order of Danneborg (Denmark)
- Royal Institute of British Architects Gold Medal (United Kingdom 1966)
- Institution of Structural Engineers Gold Medal (United Kingdom 1973).

Source:
Sydney Opera House: Nomination by the Government of Australia for inscription on the World Heritage List 2006.

(Jack) Gerhard Jacob Zunz FREng FIStructE FICE

Sir Jack Zunz was a British civil engineer and former chairman of Ove Arup & Partners. He was the principal structural designer of the Sydney Opera House.[1]

Zunz was born to a Jewish family 25 December 1923 in Mönchengladbach, Germany, but at the age of 13 the family moved to South Africa. After interrupting his studies to serve with the South African Army in the Second World War, he graduated in civil engineering at the University of the Witwatersrand, Johannesburg in 1948. He worked for a consultant and structural steelwork fabricator, going to London to join Ove Arup in 1950. In 1954, he returned to South Africa and together with Michael Lewis established an office for Arup.[2]

In 1961 Zunz returned to London as an Associate Partner and then from 1965 as a Senior Partner. He led the team which designed the roof of the Sydney Opera House.[3]

Jørn Utzon had inspired Ove Arup to take on the Sydney Opera House shells, Ove had handed the platter to Jack Zunz and now Zunz was working with his engineers to put those shells on paper in a form that could be built. But there were those who said the Opera House shells were impossible and could not be built. Candela had said so, Sydney engineers were saying so, and Ryan, the Minister for Public Works thought so. Maybe, just maybe, it could be done in steel, but concrete, you would have to be mad. Hornibrooks' most senior engineer, George Boulton, had said as much and so had other Sydney builders. To inspire others to follow you in an act of madness you have to be either a great man or a fool. But Jack Zunz was no fool. He was also an easy man to follow. His confidence never wavered, and his presence inspired confidence in the other engineers.

As John Nutt wrote many years later:

> He led the engineering team and gave it vision and direction. He was the bridge with the government, the Opera House Committee and the architect. He was able to maintain the trust of the client which is essential if a project is to be successfully implemented. There were political issues which surfaced in a blaze of publicity. He had to deal with these and give the designers room to take their technical decisions without the pressure which would lead to error. He was the guide on engineering matters for the architect. Unlike a normal structure, on the Opera House, analysis, design, construction and architecture are intertwined. Jack Zunz was the focus of this inter-relation between engineering and architecture where both come together to take on that indefinable quality of greatness which is a characteristic of this building.
>
> He brought to the job a confidence which was firmly anchored in an innovative engineering skill founded on deep technical knowledge and a creative attitude. He understood instinctively the human element and how to draw client, architect, engineer and builder into a team with a common and visionary purpose. He was courageous and optimistic, always finding a solution when difficulties arose. That requires an instinctive understanding of construction and architecture, of politics and human relationships, and a meticulous attention to detail.[4]

He was Chairman of Ove Arup and Partners from 1977 to 1984 and Co-chairman of Ove Arup Partnership, the whole Arup group, from 1984 to 1989. He was centrally involved in developing the technical skills of the firm, in increasing its geographical spread as well as creating a framework for an increasing number of talented engineers and allied professionals to develop their skills and their careers. Zunz was a consultant to Arup from

1989 to 1996 and the first Chairman of the Ove Arup Foundation. Under his guidance the Foundation initiated the Interdisciplinary Design for the Built Environment postgraduate programme at the University of Cambridge, and subsequently the LSE Cities Programme at the London School of Economics.[5]

He was a Fellow Commoner at Churchill College, Cambridge 1967-68. He has lectured widely on his projects and related topics, particularly education. He is the author or co-author of many papers. He held a number of appointments outside his firm including being Chairman of the Trustees of the Architectural Association and President of CIRIA (Construction Industry Research and Information Association).[6]

Jack Zunz died on 11 December 2018 aged 95.

Awards:

- Fellow of the Royal Academy of Engineering in 1983.
- Silver Medal of the Institution of Structural Engineers with Sir Ove Arup in 1988.
- Institution of Structural Engineers Gold medal in 1988.
- Knight Bachelor in 1989.
- Honorary Doctorate of Science from the University of Western Ontario in 1993.
- Honorary Doctorate of Engineering from the University of Glasgow in 1994.
- Honorary Doctorate of Science in Engineering from the University of the Witwatersrand in 2015.
- Honorary Fellow of the Royal Institute of Architects in 1990.
- Honorary Fellow of Trevelyan College, Durham University in 1996.[7]

Sources:

[1] https://en.wikipedia.org/wiki/Jack_Zunz

[2] **Ibid**

[3] **Ibid**

[4] **Opera House Act One 9. 357**

[5] https://en.wikipedia.org/wiki/Jack_Zunz

[6] **Ibid**

[7] **Ibid**

John Gilmore NUTT AM

John Nutt was born 19 August 1934 in Townsville, North Queensland. He commenced studying engineering in 1951 and graduated with a civil engineering degree from the University of Queensland in 1954. After a short period at the university and engineering consulting work, he took up a position in 1956 as Assistant Lecturer at the University of Manchester. For five years he carried out research on stresses and forces in building structures, receiving a doctorate in the process and taking part in the analysis of structures, involving the early use of the electronic computer developed in the early fifties by the Manchester firm of Ferranti Ltd – Ferranti marketed the first commercial computer in the world

In 1960 Nutt became Project Engineer for Ove Arup & Partners (UK) for the Barbican Redevelopment in London. Then in 1961 he started work with an Arup team on the shell roof concept and design problems, of the Sydney Opera House. The task was to define a geometry to mathematically model Utzon's shapes, it included being responsible for leading the group which designed the side shells. Following completion of the designs, he came to Australia to be the point of liaison with the builders, arriving at the end of May 1963.

In 1965 Ove Arup established a practice in Australia. Dr Nutt became a partner in 1968 and following completion of his involvement with the Opera House, worked on many important projects in Australia as well as the National Parliament House of Papua New Guinea, and the Barbican Centre, London.

In addition to his work with Arups, Dr Nutt participated in many advisory committees and lectured on practice matters at various universities; at the time of his retirement, he was Chair of Arups.

During his career Dr Nutt received the following awards:

- United Kingdom Institution of Structural Engineers Special Award 1972
- Association of Consulting Engineers Award of Excellence 1973
- President's Award, Royal Australian Institute of Architects, NSW 1991
- American Institute of Architects Honor Award 1992
- Member, Order of Australia, for services to engineering, 1992
- Doctor of Science (Honoris Causa), Macquarie University 1995
- Peter Nicol Russell Medal 1999, The Institution of Engineers, Australia.

Sources:
Opera House Act One pp. 307-308
Oral history interview with John Nutt – bio note, Sydney Engineering Heritage Committee.

Dundas Corbet Gore

Corbet Gore was Hornibrook's construction manager for Stage 2 of the Sydney Opera House.

'Dundas Corbet Gore was born in April, 1921 at Goondiwindi, NSW.

He commenced studying civil engineering at the University of Queensland in 1938. In December 1939 he joined the air force as a volunteer, and during the war flew as a navigator in Sunderland flying boats, based in Plymouth UK.

After the war he graduated in 1946, in civil engineering from the University of Sydney and joined M. R. Hornibrook Ltd where he was involved in numerous projects ranging from South Australia, New South Wales, Australian Capital Territory and New Guinea.

In 1961 he was appointed as Hornibroook's construction manager for the Sydney Opera House Stage 2 – the construction of the shells. His acceptance was on the proviso (granted) that his career path through the company would be protected'.[1]

"Gore met Jack Zunz and Utzon briefly in Sydney in March-April 1962 before setting off on a fact finding tour: to Adhesives Engineering Inc. in San Francisco about epoxy adhesives; the University of Berkley California about shell construction using pre-cast concrete ribs; big construction contractors in New York; tower cranes in Scotland and France, and in Paris, the Exhibition Hall of shell construction; Utzon's town houses in Hellebaek, Denmark, the Opera House tiles at the Hoganas' factory, and Utzon's office; and in Arup's London office.

Gore left London for Sydney on 5th July and that day Jack Zunz wrote to Malcolm Nicklin [in Sydney] begging forgiveness for not communicating earlier ... and added:

> ... we cannot help but treat Hornibrooks as part of us from now on. We have placed them in a position of trust, and we cannot treat them contractually in the same way as we would do under more normal circumstances. I have personally worked closely with Corbet over the past two to three months. Quite apart from his technical acumen and enthusiasm, we are all most taken with his attitude to the job and with his sincerity of purpose. While very often one talks about the desirability or otherwise of having a contractor in the design team, we feel that in this instance they are really with us. It would be very wonderful if we could maintain this relationship and attitude for the duration of the job'.

And when Jack Zunz wrote to Sydney a few days later on the 11th he described Gore as 'a much loved member of our team.'"[2]

'Whilst at the outset there was not even a clear idea of how the shells would be built, Gore managed the near-impossible project to a successful conclusion. In the process he solved many problems and personally contributed a number of critical innovations including the method for casting the shell segments and the concept of the erection arch for assembling the shells.

In an oral history interview for the Sydney Opera House Trust, Jack Zunz described Gore's contribution in the following terms:

> *For sheer skill, coupled with an ability to manage people and for getting the Opera House shells built, he deserves all the credit. He's a very quiet, self-effacing man, but without him, we could never have done it. We were proposing to build something which was very unusual and very difficult, and unlike most constructors, he turned round every problem and treated it in a positive way, He didn't find ways for not*

doing it, but treated a problem as a problem to be solved, which is unusual. Corbet conceived some very interesting ideas on how to put the Opera House together. … it was Corbet who came up with the ideas for the special lifting tackle. Then the idea to cast the segments with matching surfaces, which had a most profound effect on the very quality of the look of the Opera House, was also his. Certainly the decision to go ahead with these proposals was ultimately ours, but the concepts were his.

I could name a hundred and one other different things. By his personal example, with the long hours he put in and his leadership on the site, he really kept the job rolling forward. Not least in his capacity in dealing with the men, because it was a time, if ever there's not a time, when there was a great deal of industrial unrest in the construction industry. Australia is rather renowned for its industrial problems in the construction industry. And he dealt with it all magnificently.

On completion of Opera House Stage 2 in his role as a Director of Hornibrooks, he spent some unsatisfying years out of project management, finding work for the company.

In his final major project Gore managed Hornibrook's subsidiary Australian Pipeline Constructions in the construction of the second half of the Moomba to Sydney natural gas pipeline. The project encountered major problems due to the lack of necessary expertise and technology, and difficulties with the client-supplied pipe material'.[3]

On completion of this project Gore retired at the age of 63; he died in 2002.

David Messent's dedication of *Opera House Act One* is inscribed: 'This one is for Dundas Corbet Gore'.

[1] Oral history interview with Corbet Gore – bio note, Sydney Engineering Heritage Committee.
[2] Opera House Act One, pp. 269-271.
[3] Oral history interview with Corbet Gore – bio note, Sydney Engineering Heritage Committee.

Michael Elphick

Survey control of construction of the Opera House and especially of the roof was critical to a successful outcome; Michael Elphick was Arups senior surveyor.

Michael Elphick started his career in surveying articled to a Sydney surveyor. After three years he took a job for a year or two with the Hydro Electric Commission of Tasmania as surveyor on dam sites in the South West. After returning to Sydney to get his qualifications he worked on the Snowy Mountains hydroelectric Scheme for a while, before returning to Sydney where he did setting-out work for expressways.

He then responded to an advertisement saying that... Ove Arup and Partners wanted a surveyor for measuring deflections of the shell roofs of the Sydney Opera House; he was interviewed by Peter Rice, and got the job.[1]

Elphick saw as his basic survey task:

> ‘(To) provide dimensional control in the casting yard. i.e. make sure that the forms were plumb, position the "match up" segment correctly and establish reference points on each segment which would be used to assist the final positioning of the ribs.
>
> Establish reference points on the partially erected structure. The first few segments of each rib would be positioned by dimensions from these reference points.
>
> Check the position of a rib as it was being erected to enable the engineers to keep the whole rib in its best position. This involved not only finding out the rib's position, but predicting where it was heading so that corrective measures could be taken early, or at a convenient time in the erection sequence.
>
> Measure the movements of the rib during erection, including the effects of permanent stressing, release from the erection arch, and creep deflections over several months. The purpose of these measurements was twofold - it enabled the consulting engineers to check their calculations by comparing the final deflections of a rib with their predicted results and to assist in determining where to place a rib, so as to leave it in its best position.

For speed in construction the roof was erected in many different places at the same time. Should any operation be held up due to a technical difficulty, the erection crews would move to another section, thus preventing loss of time on the job as a whole. As a direct consequence, the survey staff had to be prepared for sudden changes in program. To allow for this, very tight survey control over the whole site was necessary, and because of the construction of the podium, a regular check had to be kept on permanent survey stations to see whether or not they were static’.[2]

One ingenious solution to a survey problem developed by Elphick was the upside down plum bob:

> The shell roofs stand on columns about fifty feet tall which go down through the building, and between the columns is a prestressed tie beam.
>
> The outward thrust at the top of the columns increased as tile lids were fixed to the ribs, so it was necessary to measure any movement of the columns and correct this by increasing the prestress; a high degree of accuracy was required.

The surveyors solved the problem by having a hole drilled through all the floors of the building to bedrock. They then secured a 50-foot length of piano wire to the rock and passed it up through the holes in the floors. At the top, they cut a 44-gallon drum in half and welded a tube in the centre of the base, and drilled a hole in the bottom of the drum beneath the tube.

Then they formed a big block of polystyrene into doughnut shape to use as a float which was dropped into the drum with the tube in the centre. Once the wire was run up through the tube and held in place on top of the float with a piece of wood across the top, and the drum was filled with water, 'the float lilted up with about a hundred pounds upwards thrust ... But there's no mass, so it wouldn't oscillate'. The surveyors could then use an inside micrometer to measure the distance between the top of the columns and the wire.

From then on in correspondence on shell column loads, Arups frequently referred to Michael Elphick's 'upside down plumb bob'.[3]

Sources:

[1] Opera House Act One, p. 360

[2] Opera House Act One, p. 361

[3] Opera House Act One, pp. 378-379

Appendix D

Extract from:

RESPECTING THE VISION
Sydney Opera House – a Conservation Management Plan
Fourth Edition

Alan Croker

"3.1 STATEMENT OF SIGNIFICANCE

The Sydney Opera House has been inscribed on the World Heritage List, the National Heritage List and the State Heritage Register. Each of these listings has its own Statement of Significance or Statement of Values.

The following Statement of Significance is based on that by J.S. Kerr in the 3rd edition of the Sydney Opera House Conservation Management Plan, and has been revised in response to the Sydney Opera House's inscription on the World Heritage List and on National and State Heritage registers.

The Sydney Opera House is a masterpiece of 20th century architecture and a world-renowned performing arts centre. It is universally valued for its unparalleled design, form and response to its setting; and its exceptional engineering achievements and technological innovations. It is an internationally recognised landmark, an architectural icon, a symbol of Sydney and Australia, and holds a unique place in the Australian psyche as a focus for national celebrations and events.

The design of the Sydney Opera House by Danish architect, Jørn Utzon, represents an extraordinary and inspired response to the peninsular setting in Sydney Harbour and the 1956 competition brief. Its spectacular quality as a monumental sculpture in the round, both by day and night, is enhanced by its relationship to the harbour and the city. The approach and arrival sequence, and the majestic quality of the public spaces, contained by powerful structural forms, provide an exceptional experience for users and visitors. Utzon's vision created a truly remarkable place, a structure that elevates and celebrates the human experience of the performing arts, as well as of the place itself. These attributes are true to the original design and continue to be credibly expressed.

The Sydney Opera House is a work of human creative genius; a daring and visionary experiment that has had a seminal and enduring influence on the emergent architecture of the late 20th century. This vision utilised the plastic arts (three-dimensional works or effects from sculpting, modelling and moulding), geometry and technology to create a structure at the leading edge of human endeavour, at the very edge of the possible. Utzon's original design concept, his emphasis on innovation and his unique approach to building gave impetus to a collective creativity of architects, engineers and builders. He inspired others to strive for and achieve excellence, particularly at this site.

The high-quality completion of the work by Sydney architects Hall, Todd & Littlemore, the technical support given by the internationally renowned engineering firm of Ove Arup & Partners, and the inventive contractor M.R. Hornibrook, helped make Utzon's vision a

reality. In its construction and fabric, the Sydney Opera House reflects the contemporary philosophy of assembling and creating refined forms from prefabricated components. The Sydney Opera House retains a very high level of authenticity.

At national, state and local levels, the site has significant associations with important past events, activities and uses in the site's evolution, including Aboriginal and European contact. Indigenous cultural values associated with the Sydney Opera House site relate to both tangible remains (for example, potential surviving middens or other physical relics) as well as intangible meanings, associations, stories, memories and histories. The site has been used for cultural exchange and performance since at least the 1790s and is associated with a major meeting area and place for ceremony and corroboree at the adjacent Farm Cove. Bennelong Point is a place of early contact between local Aboriginal people and European settlers and takes its name from Bennelong, a Wangal man whose hut was provided by the Europeans and located on the western side of the point. Other significant historical associations include: defence (Governor Arthur Phillip's 1788 redoubt to convict architect Francis Greenway's Fort Macquarie, 1817–1901); picturesque planning (Governor Lachlan Macquarie to Utzon); and marine and urban transport and trade (overseas shipping and local ferry wharves, tram terminal and depot).

The Sydney Opera House has an almost mythological status as a cultural icon (then and now) arising from all the above, from the high public interest in its protracted and controversial development, and from its power to attract performers, patrons and visitors on a national and international level. As Australia's pre-eminent performing arts centre, it has the ability to encourage and inspire the pursuit of excellence and innovation in those who use it or are associated with it: all are inspired to achieve an outcome 'worthy of the Sydney Opera House'.

The inscription of the Sydney Opera House on the World Heritage List in 2007 recognises its Outstanding Universal Value".

12. Acknowledgements

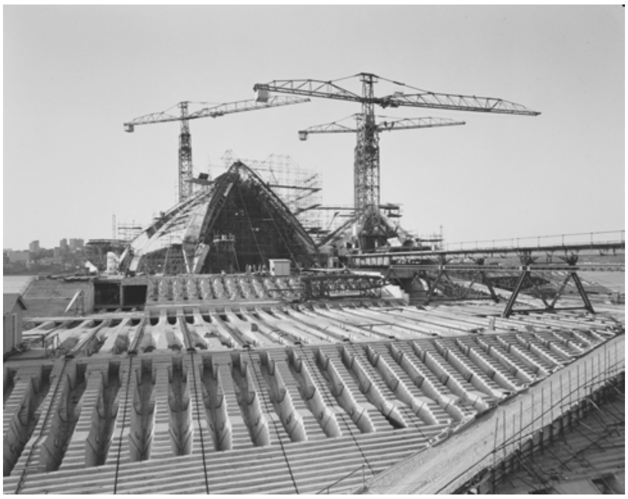
The assistance is gratefully acknowledged of: Brian Cock, Asset Planning & Information Manager, and Anne Johnstone Office Administrator - both of the Sydney Opera House, in facilitating this nomination and in the sourcing and provision of images, and of Vince Taranto in permitting the use of emails to him from Tony Gee – sadly, Tony died in February 2020.

13. Sydney Opera House Images

Attribution: *Except where otherwise indicated, images are by Max Dupain and are reproduced by courtesy of the Mitchell Library, State Library of New South Wales.*

Bennelong Point—site of Sydney Opera House

Casting yard & podium



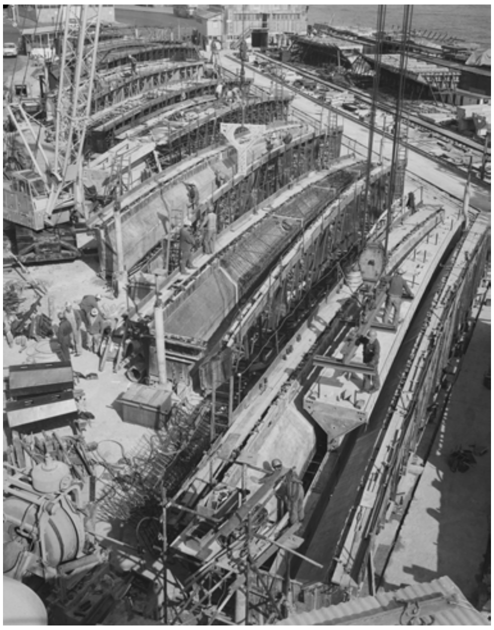
Base of grand stairs, & folded beams — *Mitchell Library, State Library of New South Wales & courtesy Department of Public Works (NSW)*

Formwork for folded beams — *Mitchell Library, State Library of New South Wales and Courtesy of Lendlease Corporation.*

Folded beam & eastern steps

Folded beams over lower concourse — *Mitchell Library, State Library of New South Wales & courtesy Cement Concrete & Aggregates Australia*


Rib casting yard


Rib casting yard


Lifting rib segment from formwork

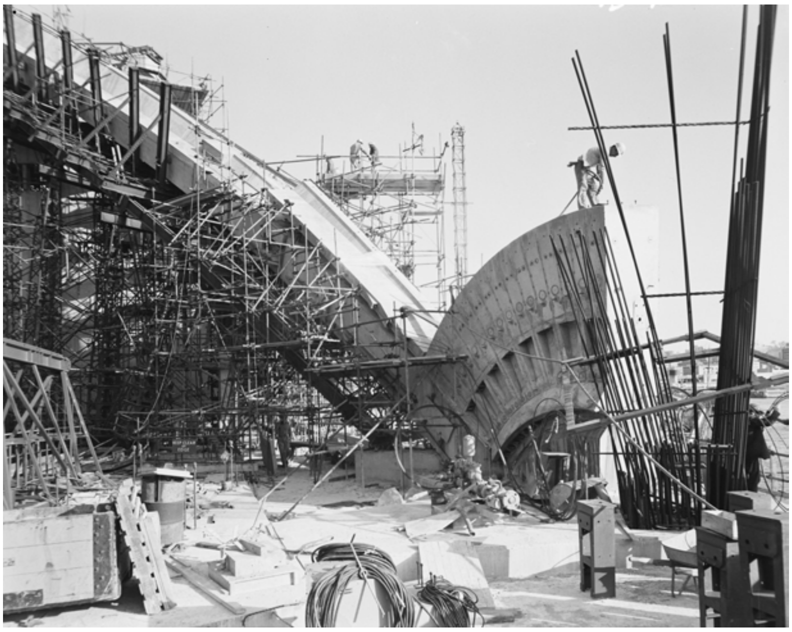

Hoisting rib segment

Constructing erection arch — *Mitchell Library, State Library of New South Wales & courtesy Department of Public Works (NSW)*

Side shell, rib pedestal & erection arch — *Mitchell Library, State Library of New South Wales & courtesy Department* of Public Works (NSW)

Placing rib segment on erection arch

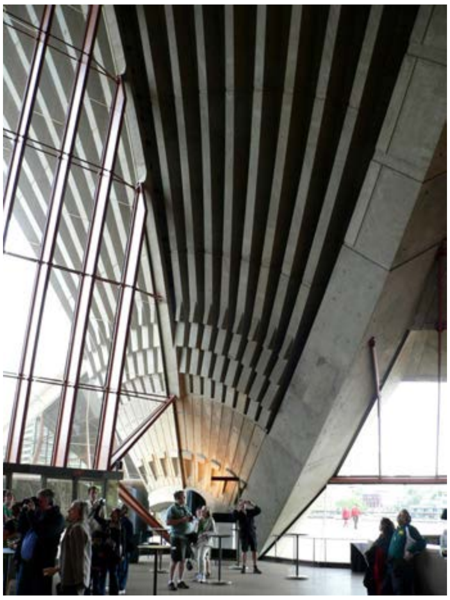
Placing ridge segment (segment to be turned)



Rib pedestal

‘Rib fans’, northern foyer

‘Rib fan’

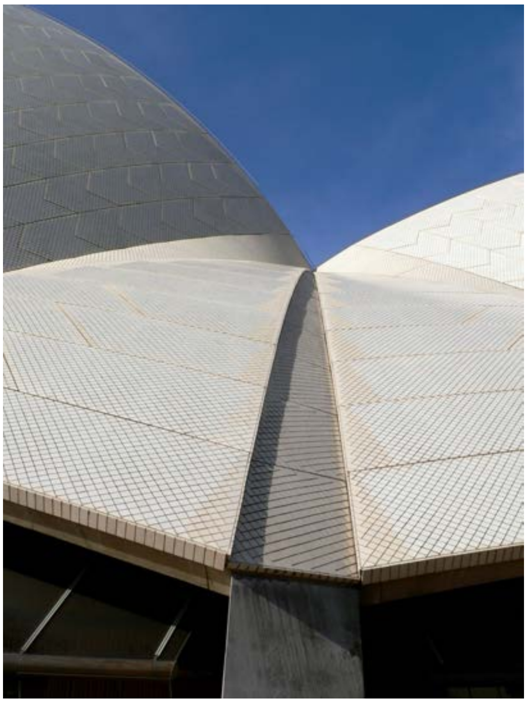


‘Rib fan’ & glass wall —
Michael Clarke

Interior restaurant

Sculpture of ‘Spherical Solution’ - *Michael Clarke*

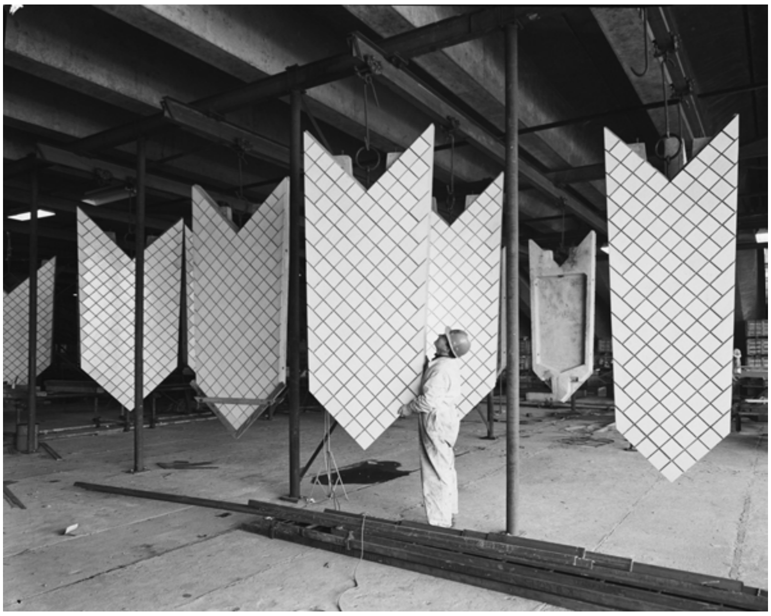
Main roof & side shell



Junction of two side shells —
Michael Clarke

Northern louvres

Forming tile lid — Mitchell Library, State Library of New South Wales & courtesy Sydney Opera House



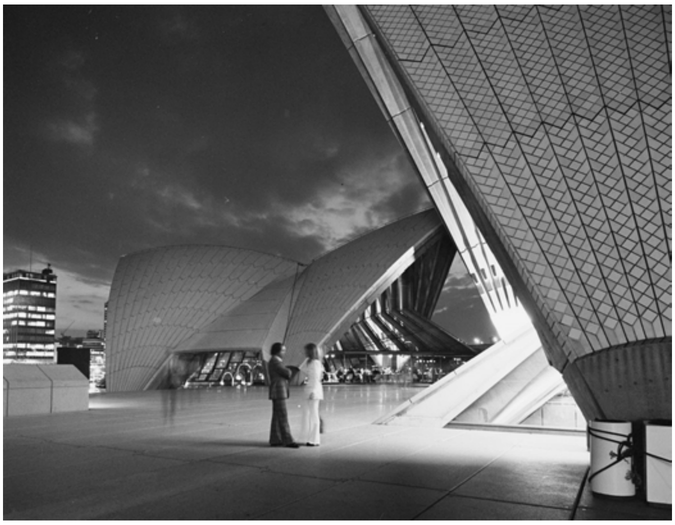
Curing tile lids

Installing tile lids

'Tile lid fan'— *Michael Clarke*

Bennelong Restaurant

Glass walls, Bennelong Restaurant. *Image by Patrick Crowe, courtesy Mitchell Library, State Library New South Wales*



Bennelong Restaurant

Glass roof & walls, northern foyer

Glass roof, northern foyer

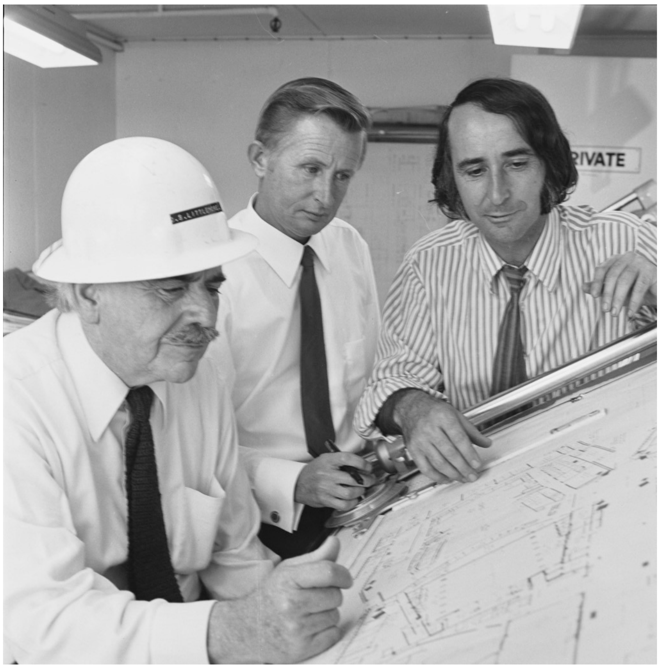
Control room. *Courtesy of Mitchell Library, State Library of New South Wales & of Amalgamated Wireless Australasia Pty Ltd*

Survey observation pillar — *Michael Clarke*

Michael Lewis, Ove Arup & Jack Zunz — Mitchell Library, State Library of New South Wales & courtesy Department of Public Works (NSW)

Corbet Gore (on left) - *Mitchell Library, State Library of New South Wales and courtesy Department of Public Works (NSW)*

Jørn Utzon — courtesy Dennis Wolanski Archives, Sydney Opera House



David Littlemore, Lionel Todd & Peter Hall

Surveyors